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Effects of boating activities on aquatic vegetation in the Stockholm archipelago, Baltic Sea

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Abstract

The aquatic vegetation in 44 similar shallow and sheltered inlets exposed to different kinds of disturbances by boating was studied in a rocky archipelago in the Baltic Sea. The results indicate that both recreational boating activities and traffic by medium sized ferryboats may cause significant changes in community composition and have significant negative effects on species richness and the development of the macrophytic vegetation at greater depth. Changes in inlet morphology by dredging and increases in resuspension and turbidity by wave-action from boats were most probably the major factors contributing to the demonstrated differences in the vegetation between inlets. In inlets used as harbours for private boats (marinas) or adjacent to ferryboat routes, vegetation cover and species richness declined significantly more with depth than in reference inlets not exposed to disturbance by boating activities. In marinas, turbidity was significantly higher than in reference inlets. Accordingly, a canonical correspondence analysis showed that the abundance of species sensitive to poor light conditions, such as *Chara* spp. and *Ruppia* spp. were negatively correlated with marinas while *Myriophyllum spicatum* and *Ceratophyllum demersum* that are common in nutrient rich turbid habitats were positively correlated with marinas. Mechanical disturbance by propellers may also have contributed to the results, disfavours *Potamogeton pectinatus* compared to similar caulescent species in marinas. *Chara tomentosa* and *Najas marina* that are exposure sensitive mud thriving species were negatively correlated with inlets adjacent to ferryboat routes, while the macroalga *Fucus vesiculosus* that is dependent on clean substrate for successful recruitment was positively correlated with inlets adjacent to ferryboat routes. It is important to explore further the effects of boating activities in these habitat types, since the studied inlets sustain a high diversity of both plants and invertebrates and provide highly significant recruitment areas for coastal fish in the Baltic Sea.

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Keywords: recreational boating; ferry traffic; brackish community composition; charophytes; multivariate analyses; *t*-value biplot

1. Introduction

Aquatic vegetation has important functional qualities in coastal ecosystems. Vegetative cover contributes to primary production, sediment stabilisation and filtration of land runoff (Duarte, 2000). Macroscopic vegetation

also contributes to physical structure in aquatic environments and provides feeding and nursery habitat for many species of invertebrates and fish (Orth et al., 1984; Lubbers et al., 1990; Grenouillet and Pont, 2001), thereby being a crucial element in sustaining aquatic biodiversity. Various coastal ecosystems are strongly affected by anthropogenic disturbances and detrimental effects on community structuring organisms caused by nutrient enrichment or excessive resource extraction are commonly reported from littoral zones world wide (e.g. Rogers, 1990; Short and Wyllie-Echeverria, 1996;

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van der Putten, 1997; Jansson and Dahlberg, 1999; Cloern, 2001). Far less is known about the magnitude and distribution of near-shore impacts by recreational activities and boating, but effects of such disturbances receive increasing attention (e.g. Burdick and Short, 1999; Shaefer, 1999; Kennish, 2002). This study presents observational data of effects of recreational boating activities and traffic by ferryboats on aquatic vegetation in an extensive rocky archipelago area in the Baltic Sea.

The Baltic Sea is practically without tidal fluctuations and brackish, with a clear gradient in salinity from south (Baltic Sea proper, salinity 6–7) to north (Bothnian Sea, salinity ca. 5; Bothnian Bay, salinity <2). A mixture of flowering plants and macroalgae of both freshwater and marine origin characterise the aquatic vegetation (Snøeijls, 1999). Due to glacial uplift, the rocky coasts in the Baltic display an abundance of islands and shallow sheltered inlets in different stages of succession: from relatively exposed rocky sites dominated by macroalgae to soft-bottom water bodies almost cut off from the sea, dominated by flowering plants and charophytes (Munsterhjelm, 1997). These shallow inlets are the main habitat for several brackish water plants and endangered charophytes (Blindow, 1994, 1995; Wallström and Persson, 1999). The occurrence of dense vegetation is one of the main factors attracting spawning adults, larvae and juvenile fish (Urho et al., 1990; Sandström and Karås, 2002a).

The archipelagos in the Baltic Sea experience the traffic of a large number of smaller recreational boats and ferries of different sizes. The ecologically important shallow and sheltered inlets are commonly used as marinas for private boats. Frequent and fast ferryboats have an increasing presence among remote islands that lack other transport alternatives. Changes in the distribution, development and species richness of macroalgae have been demonstrated along routes for larger car-ferries (1000–3500 passengers) in a Finnish archipelago (Rönnberg, 1981) and the car-ferries potentially also influence invertebrate (Fagerholm, 1978) and fish communities (Rajasilta et al., 1999). Little is known of the effects of the much more frequent traffic of medium-sized ferryboats (<350 passengers) and private boats. These disturbances also cover much larger areas than those from the car-ferries which are restricted to a few routes.

The present objective was to study local impacts of boating on the aquatic vegetation in shallow and sheltered inlets in a rocky archipelago area. Specifically, effects on the vegetation associated with marinas for smaller boats and routes for medium-sized ferryboats were investigated by comparison with physically similar reference inlets not apparently affected by boating. The main hypotheses were: (1) that frequent traffic by small recreational boats should increase turbidity from resuspension so that marinas demonstrate a diminished development of the vegetation at greater depths and

reduced amounts of shading sensitive species, such as *Chara* spp. and *Ruppia* spp.; (2) that ferryboats should increase wave erosion and mechanical stress so that inlets adjacent to ferryboats demonstrate reduced amounts of species that thrive in loose and muddy bottoms, such as *Chara tomentosa* and *Najas marina*; and (3) that dredging should be associated with inlets disturbed by boating and should be detrimental to deeper growing vegetation.

2. Material and methods

2.1. Study site

The study was performed in the Stockholm archipelago, an extensive area on the Swedish coast in the NW Baltic proper that consists of ca. 30,000 islands and small islets (Fig. 1). Glacial uplift in the area is around 4 mm per year and this determines a predictable morphological and floristic development of inlets in the archipelago that reflects the transformation of sea and aquatic communities to land and terrestrial vegetation. The studied inlets had an area of 1–11 ha and were shallow with mean depths ranging from 0.6 to 2.9 m and with no depth exceeding 5 m. All inlets were sheltered but influenced by open sea and exposure to different degrees. The flora was dominated by soft-bottom communities, but with intrusions of rocky-bottom community types. Salinity in the central Stockholm archipelago fluctuates between 4 and 7. Munsterhjelm (1997) showed that changes in salinity due to increased freshwater influence during the land-uplift succession is not a driving force in the succession of the vegetation in these types of inlets.

2.2. Data collection

The vegetation in inlets situated in the central archipelago was surveyed between mid July and late August 2002 (Fig. 1). Fifteen inlets were studied in each of the categories: marinas (inlets used as harbours for small boats), ferry routes (inlets adjacent to ferryboat routes) and reference inlets (inlets not subjected to apparent boating activities). Inlets that were significantly influenced by anthropogenic disturbances other than boating were excluded. A free diver visually estimated the percentage cover of different species of the macrophytic vegetation in 5-m plots adjacent to each other along transects. Transects were placed parallel to the opening of each inlet in 30 m intervals, from the opening to the end of the inlets. Thus, the number of plot per inlet was dependent on inlet size. Only the vegetation growing within 0.5 m on either side of the transect line was considered. For all plots (5 × 1 m), depth and GPS position was recorded. Water turbidity was measured at

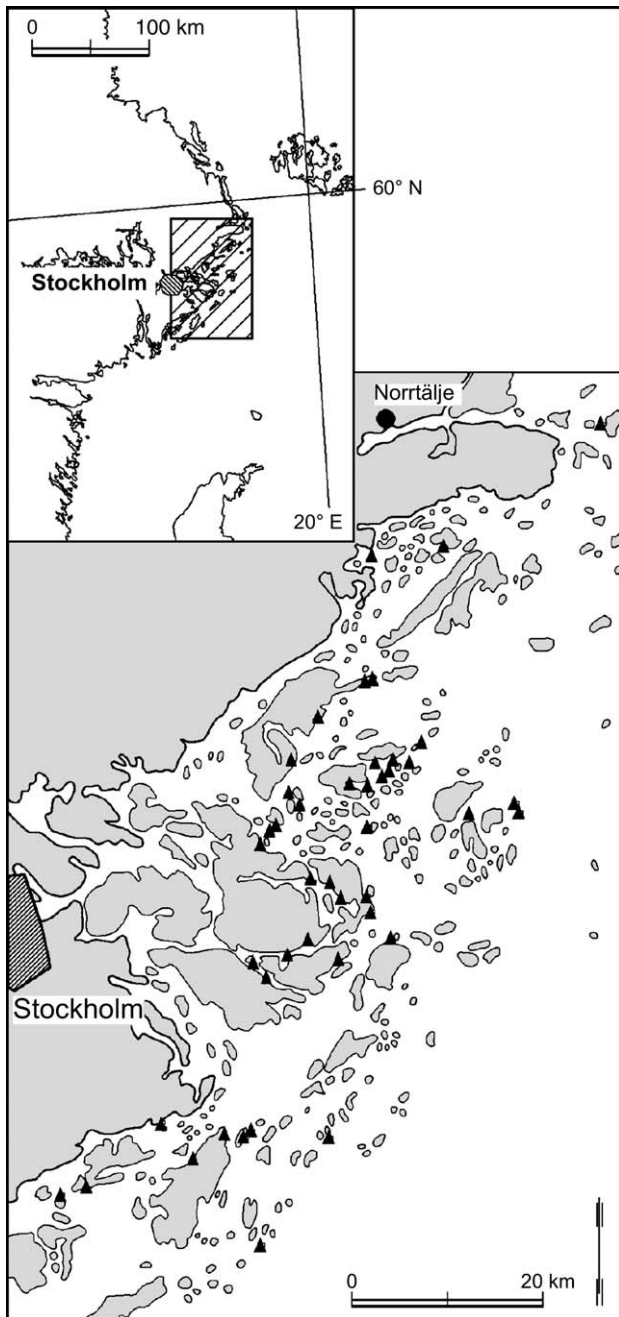


Fig. 1. Maps showing the general location of the study area, Stockholm archipelago, Sweden (top map), and the specific outlets studied (bottom map—triangles).

3–4 sites within each inlet. The turbidimeter was calibrated with formacin and measured turbidity in NTU (nephelometric turbidity units). For all inlets, area, shoreline length and opening width were calculated using digital nautical charts obtained from the Swedish National Maritime Administration. In all marinas also the total number of berth-places for medium sized boats (ca. 5–7 m long) were counted. Dredging activities were noted using data from permission records at the municipal administration board combined with observations in

the field. One of the reference inlets was excluded from further analyses due to a massive occurrence of loose-lying drift algae, forming an impermeable layer that covered the inlet at the time of the vegetation survey.

The included inlets differed greatly in geometric dimensions such as opening width, area and shape. Since these properties largely affect exposure, which in turn should influence the proportion of soft- and hard-bottom vegetation in these inlets, were different exposure indices and the shape of the inlets estimated to be included as co-variables in the analyses. Exposure for each inlet was estimated using two exposure indices with distinctly different properties. First, the exposure area index (E_a) that estimate exposure only considering the geometric dimensions of the inlets was calculated using the formula: $E_a = 100A_tA_i^{-1}$, where A_t is the area at the opening (opening depth times opening width) and A_i is the area of the inlet (all measures expressed in km^2) (Pilesjö et al., 1991). A high value indicates that the inlet has a large opening relative to inlet area and therefore is more susceptible to incoming waves. Second, the wave impact (WI) was derived from wind data and fetch, which estimates the distance from which waves can potentially collect wind energy before reaching a site. Fetch was calculated in 16 directions for each single plot using a geographic information system (GIS) (Wave-Impact software; M. Isæus, pers. comm.). Wave impact was then calculated for each direction (WI_d) according to the formula: $WI_d = F((\sum(U^2))n^{-1})^{0.5}$, where F is the fetch, U is the wind speed and n is the number of occasions this wind speed was recorded (wind data from Landsort, Stockholm archipelago, recorded 1991–1995, 4 times per day). The formula gives stronger winds heavier weight. Two derivatives of WI were calculated for use in the analyses: (1) by calculating the mean of the 16 WI_d values (WI_{mean}) for each plot, which estimates a general mean exposure and (2) by choosing the largest of the 16 WI_d values (WI_{largest}), which estimates the strongest exposure under extreme conditions. These two properties of wave impact can be expected to affect the vegetation differently. Shape of the shoreline was calculated for each inlet by comparing the relation between shoreline length and inlet area with that of a circle using the formula: $\text{Shape} = L_s((A_i\pi^{-1})^{0.5} \times 2000\pi)^{-1}$, where L_s is shoreline length and A_i is the area of the inlet. Thus, a high value indicates a highly lobated shoreline, which should promote species that thrive in the border zone between land and water, such as *Phragmites australis*.

2.3. Data analysis

Differences in physical characteristics between the inlet types (marinas, ferry routes and reference inlets) were analysed by one-way ANOVAs. Tested physical characters included: mean inlet depth, opening depth,

opening width, inlet area and the shape of the shore in the inlets. ANCOVA was used to test for significant differences in vegetation characteristics between the inlet types, including total vegetation cover and species richness as dependent factors. Since individual plots were sub-samples of a particular inlet, inlets were nested within inlet type. Nesting made the ANCOVA models highly complex and only the co-variables depth and exposure that were considered the most important were therefore included. WI was used as the measure of exposure since E_a was calculated for each inlet and therefore had no variance within the nested factors (single inlets). Depth and inlet type were crossed in the analyses to detect differences between the inlet types that depended on depth. Co-variables that showed no tendencies to affect the dependent variables ($p > 0.50$) were omitted from the analyses. In all ANCOVA and multivariate analyses (see below), only the WI index (mean or largest) with best explanatory power was used to avoid correlations between co-variables. ANCOVA was also used to test for differences in turbidity between the inlet types.

Differences in species composition between the inlet types were tested by a canonical correspondence analysis (CCA) using species cover as dependent variables and inlet type, depth, exposure (E_a , WI), inlet position

(longitude, latitude) and shape of the shore as explanatory variables (CANOCO 4.0; ter Braak and Šmilauer, 1998). The interaction term between fetch and E_a was also included, since the morphology of the inlets should greatly influence the effect of incoming waves (modelled by WI). A preliminary detrended correspondence analysis indicated a strong unimodal response of species variance to the environmental variables. Since nesting was not possible in the CCA, it was performed on a pooled data set constructed by calculating mean abundance for each species in 0.5-m depth intervals (0–2.5 m depth), for each inlet. The statistical significance of single species responses to the environmental variables was examined by producing a t -value biplot from the CCA. The t -value biplots show graphically if an environmental variable contributes significantly to the multiple regression of a particular species along the two first axes produced by the CCA.

3. Results

In total 26 species were recorded in 4715 plots from the 44 inlets (Table 1). Inlets used as marinas harboured a median of 65 boats (mean = 111) and inlets adjacent to ferryboat routes were trafficked by 10–40 medium-sized

Table 1
List of species found in the studied inlets, Stockholm archipelago, Sweden

	Abbreviation	Distribution ^a	Life-form
Flowering plants			
<i>Callitriche hermaphrodita</i> L.	Cher	f, b	submerged, caulescent
<i>Ceratophyllum demersum</i> L.	Cdem	f, b	submerged, caulescent
<i>Lemna trisulca</i> L.	Ltri	f, b	floating-leaved
<i>Myriophyllum sibiricum</i> Kom.	Msib	f, b	submerged, caulescent
<i>Myriophyllum spicatum</i> L.	Mspi	f, b	submerged, caulescent
<i>Najas marina</i> L.	Nmar	f, b	submerged, caulescent
<i>Phragmites australis</i> (Cav.) Steud.	Paus	f, b	emergent
<i>Potamogeton filiformis</i> Pers.	Pfil	f, b, m	submerged, caulescent
<i>Potamogeton pectinatus</i> L.	Ppec	f, b, m	submerged, caulescent
<i>Potamogeton perfoliatus</i> L.	Pper	f, b	submerged, caulescent
<i>Ranunculus baudotii</i> Godr. ^b	Rbau	f, b	submerged, caulescent
<i>Ranunculus circinatus</i> Sibth.	Rcir	f, b	submerged, caulescent
<i>Ruppia cirrhosa</i> (Petagna) Grande	Rcir	b, m	submerged, caulescent
<i>Ruppia maritima</i> L.	Rmar	b, m	submerged, caulescent
<i>Schoenoplectus/Scirpus</i> ssp.	Scho/Scir ssp	–	emergent
<i>Zannichellia palustris</i> L.	Zpal	f, b, m	submerged, caulescent
Algae			
<i>Chara aspera</i> Deth. ex Willd.	Casp	f, b	attached, erect
<i>Chara baltica</i> Bruz.	Cbal	b	attached, erect
<i>Chara canescens</i> Loisel	Ccan	b	attached, erect
<i>Chara horrida</i> Wahlst.	Chor	b	attached, erect
<i>Chara tomentosa</i> L.	Ctom	f, b	attached, erect
<i>Chorda filum</i> (L.) Stackh.	Cfil	b	attached, erect
<i>Fucus vesiculosus</i> L.	Fves	b	loose-lying/attached, erect
<i>Monostroma balticum</i> Wittr. ^b	Mbal	b	loose-lying
<i>Tolypella nidifica</i> (Müll.) A. Braun.	Tnid	b	attached, erect
<i>Vaucheria dichotoma</i> (L.) Mart.	Vdic	f, b	mat-forming

^a f = freshwater, b = brackish, m = marine.

^b Uncertain species status.

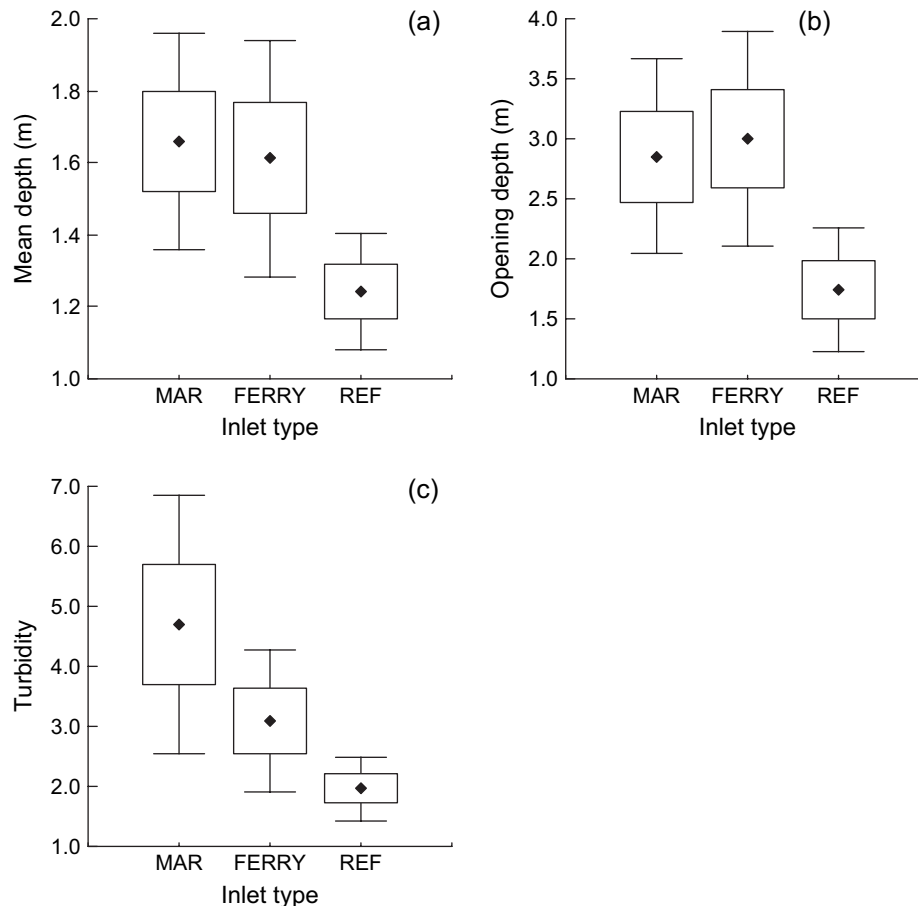


Fig. 2. Means for (a) mean depth, (b) opening depth and (c) turbidity in shallow inlets used as marinas for smaller boats (MAR), inlets adjacent to ferry routes for medium sized ferries (FERRY) and morphologically similar reference inlets (REF). Boxes denote ± 1 SE and error bars 95% confidence intervals.

ferries per day. All inlets used as marinas and six inlets adjacent to ferry routes had been dredged at least once the past 10 years, while no reference inlets showed signs of dredging. Mean depth and opening depth were significantly shallower in the reference inlets, compared with the inlets affected by boating ($p < 0.05$) (Fig. 2a and b). For the other physical characters tested (opening width, inlet area and shape of the shore), there were no statistically significant differences between the inlet types. WI and E_a showed no tendencies to affect turbidity in an ANCOVA analysis ($p > 0.50$), and co-variables were therefore omitted in the statistical model of turbidity. A one-way ANOVA revealed that there was a statistically significant difference in turbidity (NTU) between the inlet types ($p < 0.05$) (Fig. 2c). Further, a post hoc test showed that marinas were more turbid than the reference inlets (Fisher's HSD test, $p < 0.05$).

Analyses of vegetation characteristics showed that there were significant differences in total vegetation cover and species richness between the inlets, and a significant effect by wave impact (WI) such that both species richness and vegetation cover increased with increasing exposure (Table 2). In all ANCOVA analyses, WI_{mean}

described the dependent variables better than $WI_{largest}$ and $WI_{largest}$ was therefore omitted from the analyses. While there was no statistically significant effect on any of the vegetation characteristics by the main factor inlet type, both total vegetation cover and species richness were significantly affected by the interaction between inlet type and depth (Table 2). Calculating least square means for total vegetation cover and species richness in half-meter depth intervals showed that the significant interaction effect depended on the fact that the reference inlets had a higher vegetation cover and more species at greater depth than the inlets affected by both types of boating impacts (Fig. 3).

The canonical correspondence analysis (CCA) explained 28.4% of species variance in all 44 inlets (Monte Carlo permutation test of all ordination axes, $p < 0.005$). The first three ordination axes were most important and described 76.4% of the variance in species data explained by the environmental variables. Exposure modelled as the interaction between $WI_{largest}$ and E_a contributed most to the explained variance in species data, but also marinas, presence of ferry routes and depth contributed largely (Table 3). Accordingly,

Table 2

ANCOVA results for differences in vegetation characteristics between inlets used as marinas for smaller boats, inlets adjacent to ferry routes for medium sized ferries and morphologically similar reference inlets

	Total vegetation cover (arcsine transform.)			Species richness (square-root transform.)		
	df	F	p	df	F	p
Inlet (Inlet type)	41	68.2	<0.001	41	22.1	<0.001
Inlet type	2	0.7	0.51	2	2.6	0.08
WI _{mean}	1	124.6	<0.001	1	26.4	<0.001
Depth	2	13.3	<0.001	2	11.5	<0.001
Depth × Inlet type	1	9.6	<0.01	1	11.3	<0.001

Inlet was nested within inlet type. Depth and wave impact (WI_{mean}) are included in the model as continuous co-variables.

intra-set correlations between the environmental variables and the axes show that axis 1 mainly was related to exposure (WI_{largest} and E_a), axis 2 to inlet type (marina and reference inlet) and axis 3 to depth (Table 3). This shows that exposure, boating activities and depth correlate with differences in species abundances between the inlets. The *t*-value biplot showed that inlet type (marina or ferry route) had a statistically significant influence on ca. a third of the present species in the CCA (Fig. 4). Notably, there was a lower abundance of two *Chara*- and *Ruppia*-species in inlets used as marinas and of *Chara tomentosa* and *Ruppia maritima* in inlets adjacent to ferry routes. All species that were significantly correlated with inlets disturbed by boating and the direction of the relations are summarised in Table 4. Effects of reference inlets are not included in the statistical analysis since it auto-correlate symmetrically with the other inlet types.

4. Discussion

The results show that recreational boating and traffic by medium sized ferryboats appear to have significant effects on aquatic vegetation. The vegetation in inlets used as marinas or in inlets adjacent to ferryboat routes

had pronounced declines in species richness and percentage cover with depth that were not present in reference inlets. There were also significant differences in species-specific abundance between the three inlet types. The aquatic vegetation in the Baltic Sea is already highly affected by anthropogenic disturbances. Local degeneration of macrophytic communities by industrial pollution or heavy loads of sewage have been reported from all over the Baltic Sea (Schramm, 1996; Jansson and Dahlberg, 1999). Decreased maximum depth limits of seaweeds and general increases of ephemeral algae in exposed areas not affected by local point sources indicate that there are also large-scale effects of eutrophication on the Baltic vegetation (Kautsky et al., 1986; Eriksson et al., 1998; Rönnberg and Mathiesen, 1998). While the documented human influence on the vegetation in the Baltic Sea mainly has been described for macroalgae in connection with nutrient enrichment, this study shows that activities associated with boating also may be of significant importance for both flowering plants and macroalgae in the Baltic Sea.

Boating can be assumed to affect vegetation directly by increased water movement and physical effects or indirectly by related activities. Increased water movement has several consequences: (1) increased wave-action enhances drag and tear on plant tissue; (2) elevated

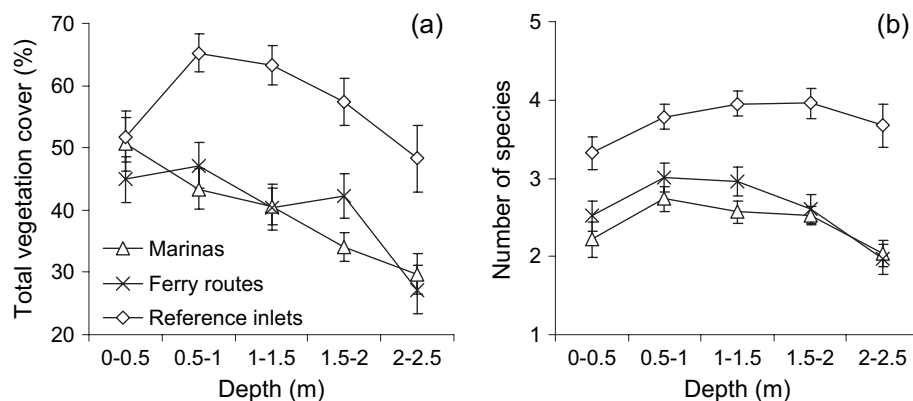


Fig. 3. Least square means for (a) total vegetation cover and (b) species richness in shallow inlets used as marinas for smaller boats, inlets adjacent to ferry routes for medium sized ferries and morphologically similar reference inlets. Least square means were calculated in depth intervals of 0.5 m, using the exposure index WI_{mean} as co-variable. Error bars denote 95% confidence intervals.

Table 3

Contribution of the environmental variables to total explained species variance by a Canonical Correspondence Analysis performed on the vegetation in all 44 inlets, and intra-set correlations between variables and ordination axes 1, 2 and 3 (W_{largest} and E_a are different types of wave exposure indices)

Variable	Explained variance (%)	<i>P</i>	<i>F</i>	Correlation with axes		
				Axis 1	Axis 2	Axis 3
$W_{\text{largest}} \times E_a$	26.3	<0.01	17.27	−0.62	−0.07	0.13
Marinas	17.5	<0.01	11.19	0.30	0.47	0.18
W_{largest}	12.5	<0.01	9.80	−0.54	−0.31	0.12
Depth	12.5	<0.01	8.84	−0.23	0.23	0.38
Ferry routes	11.3	<0.01	8.31	−0.31	0.08	−0.34
E_a	7.5	<0.01	5.97	−0.60	0.05	0.10
Latitude (E–W)	6.3	<0.01	4.26	0.23	−0.08	−0.21
Shape of shoreline	3.8	<0.01	3.36	0.20	−0.21	0.06
Longitude (N–S)	2.5	<0.05	1.91	0.31	0.18	−0.28
Reference inlets ^a	–	–	–	0.01	−0.52	0.16

^a Contribution to total explained variance was not calculated for the reference inlets, since reference inlets auto-correlate with ferry routes and marinas.

turbidity due to resuspension reduces light availability; and (3) removal of sediment from the bottom substrata and vegetation can alter habitat and uproot plants. Direct physical effects include impacts of boat hulls, propellers and shading. Indirect effects include impacts of dredging activities, moorings and docks, as well as pollution by boat motors and human waste. Rönnerberg (1981) showed that increased water movement changed depth distributions of macroalgae along routes of larger ferries in the Åland and Turku/Åbo archipelago, SW Finland. Increased wave action moved the upper limits of ephemeral algae higher by frequent wash of the shores and moved the *Fucus vesiculosus*-belt deeper by increased wave and ice erosion and by partly exposing sediment covered rock surfaces. Detrimental effects on coastal vegetation by increased water movement were reported by Hartig et al. (2002), who suggested that erosion from waves generated by boat traffic contributed to reported massive losses of salt-march vegetation in Jamaica Bay, New York City. Indirect effects of recreational boating have been demonstrated by Burdick and Short (1999), who showed that shading from docks caused local destruction of eelgrass beds in coastal waters of Massachusetts.

Comparing species-specific differences between inlet types in this study with changes in community composition during land-uplift succession in similar inlets in Finland (Munsterhjelm, 1997) suggests two general patterns. In our analyses, species that commonly dominate early inlet stages as well as deeper communities (>0.6 m depth) were associated with marinas (*Ceratophyllum demersum* and *Myriophyllum spicatum*). Species that commonly dominate late inlet stages as well as shallow communities (<0.6 m depth) were significantly less abundant in marinas (*Chara aspera*, *Potamogeton pectinatus* and *Ruppia maritima*) and along ferryboat routes (*Chara tomentosa* and *Najas marina*), compared to reference inlets. Thus, it seems that

recreational boating influences the vegetation by negative effects on species that dominate shallower communities and late stages in the land-uplift succession. All inlets used as marinas showed signs of dredging activities. It is therefore probable that changes in inlet morphometry by dredging contribute to the observed differences in species composition between inlet types. Dredging counteracts the natural land-uplift process and should therefore affect species that dominate late stages in the land-uplift succession negatively. Opening and mean depths were significantly deeper in the inlets used as marinas or adjacent to ferry routes, and like boating, signals greater water exchange and effects upon the bottom substrate. This may reflect that humans should favour deeper inlets for marinas. However, many of the studied marinas would in their natural state have been cut off from the sea without significant and continuous dredging activities.

Water turbidity was significantly higher in marinas compared with reference inlets and there were significant declines in species richness and vegetative cover in inlets affected by boating, due to a diminished development of the vegetation with depth. It is therefore likely that the depth dependent effects on vegetation characteristics and species composition in marinas and ferry routes are related to lowered light conditions in the water due to increased sediment resuspension by boats. Boat traffic has been correlated with up to a 50% increase in turbidity in lakes and rivers (Garrad and Hey, 1988; Anthony and Downing, 2003). Certainly, inlet types affected by boats were deeper (larger mean depth), but depth was incorporated as a co-variable in all analyses and the significant differences in species composition between inlet types should therefore reflect an upward movement of the vegetation in marinas and along ferryboat routes.

Species-specific trends further indicated that the high turbidity in marinas affected the vegetation. Charophytes

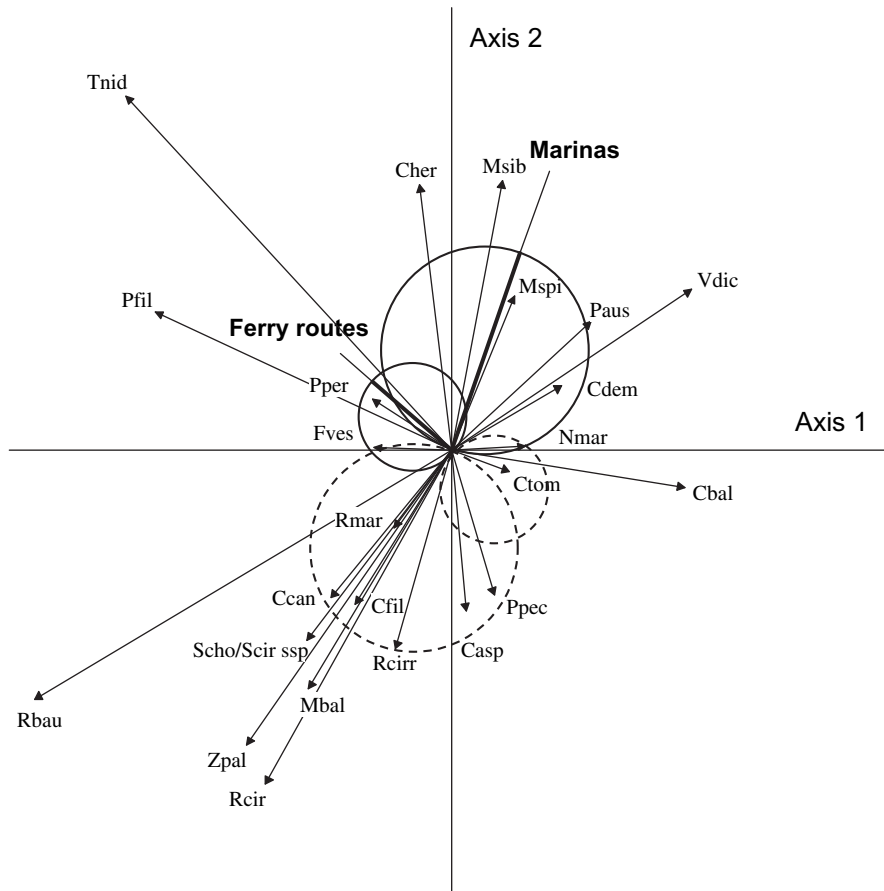


Fig. 4. Canonical correspondence analysis t -value biplot of the vegetation in 44 shallow inlets in the Stockholm archipelago, showing the critical t -value of 2 in ordination space (approximating $p = 0.05$) for each species (arrows) and the canonical regression coefficients for the environmental variables ferry routes and marinas (lines). The points on the regression lines where the lines change from thick to thin indicate the t -ratios of the environmental variables. The solid circles (Van Dobben-circles; ter Braak and Šmilauer, 1998) are constructed using the line-segments between the points for the t -ratios of the environmental variables and the origin as diameter. The dotted circles are the mirror image of each of these circles. Species whose t -values lie within the solid circles react statistically significantly positive to the particular environmental variable. Similarly, species whose t -values lie within the dotted circles react statistically significantly negatively to the particular environmental variable. For species abbreviations, see Table 1.

were negatively associated with boating activities in our study and are generally considered typical clear-water plants that are sensitive to poor light conditions (Krause, 1981; Coops, 2002). Caulescent angiosperms often can compensate effectively for poor light availability by shoot elongation, canopy formation and rapid growth during spring and therefore have a generally higher maximum depth distribution than charophytes in turbid lakes (Blindow, 1992; Middelboe and Markager, 1997). Among the caulescent plants, *Potamogeton pectinatus*, *Ruppia cirrhosa* and *R. maritima* were less common in marinas than in the reference inlets, while *Ceratophyllum demersum* and *Myriophyllum spicatum* were more common in marinas. *R. maritima* is very sensitive to poor light conditions and can respond negatively to only minor increases in turbidity (reviewed by Kantrud, 1991). A comparable susceptibility to increased turbidity was demonstrated for *R. cirrhosa* in coastal areas in Finland and the Netherlands by Verhoeven (1980), who suggested that *Ruppia* spp. can develop normally only in clear

water. *C. demersum*, *M. spicatum* and *P. pectinatus* are all highly competitive species with high production rates (Kautsky, 1988). Different responses to mechanical damage such as cutting by propellers may have contributed to the different trends in abundance of these species in our study. Clipping experiments by Cohen et al. (1986) demonstrated that *M. spicatum* regenerated from below the damaged point, while *P. pectinatus* regenerated from the roots. Thus, Kantrud (1990) suggested that *M. spicatum* would be favoured over *P. pectinatus* when competition for light is combined with grazing. We suggest that the same effect on selective conditions changing competition in favour of *M. spicatum* over *P. pectinatus* could be generated by boating, when increased resuspension resulting in increased turbidity and competition for light is combined with frequent disturbance from cutting by propellers. *C. demersum* should be highly tolerant to cutting and uprooting by propellers, since it thrives free floating and mainly regenerates by fragmentation. Accordingly, Cragg et al. (1980) reported

Table 4

Total species variance explained by Canonical Correspondence Analysis (CCA), for species with a statistically significant ($p < 0.05$) relation to marinas or ferry routes ((+) or (–) indicate if the different inlet types contributed significantly positively or significantly negatively to the multiple regression of the particular species in the CCA)

Marinas (+)	Explained variance (%)
<i>Ceratophyllum demersum</i>	29.05
<i>Myriophyllum spicatum</i>	25.34
Marinas (–)	
<i>Chara aspera</i>	10.37
<i>Chara canescens</i>	17.42
<i>Chorda filum</i>	22.91
<i>Potamogeton pectinatus</i>	15.41
<i>Ruppia cirrhosa</i>	24.17
<i>Ruppia maritima</i>	37.82
Ferry routes (+)	
<i>Fucus vesiculosus</i>	38.64
<i>Potamogeton perfoliatus</i>	37.7
Ferry routes (–)	
<i>Chara tomentosa</i>	54.22
<i>Najas marina</i>	37.99

Note: Statistical significance inferred from the approximations in Fig. 4.

that *P. pectinatus* disappears when recreational boating results in highly increased turbidity levels.

Changes in species composition in inlets adjacent to ferry routes seemed closely connected to increases in water movement. *Chara tomentosa* and *Najas marina* that were negatively correlated with ferryboat traffic are typical mud-bottom species that thrive in stagnant water and are the most sensitive of all associated species to exposure, while *Potamogeton perfoliatus* that was positively correlated with ferryboat traffic requires circulating water (Munsterhjelm, 1997). In a recent long-term study of the effects of ferry traffic on rocky-shore algal communities in the Åland archipelago, Roos et al. (in press) found that regular strong water movements from larger car-ferries seemed to affect algal vegetation positively, probably by keeping the bottoms free from sediment and drift algae. In contrast to our results, species richness was highest close to ferry routes, primarily because of an increase in the number of red algal species. However, while Roos et al. (in press) studied relatively exposed hard bottom communities, our results are from very sheltered communities dominated by soft bottoms. Rocky-shore macroalgae are dependent on bare substrate for attachment, and negative effects of sedimentation on the establishment and development of macroalgal communities have been demonstrated in both the Mediterranean (Airolidi and Cinelli, 1997) and the Baltic Sea (Eriksson, 2002). Rooted flowering plants and charophytes that normally occur in sheltered locations with easily disturbed loose bottoms, should be more sensitive to drag and tear from artificial exposure and more tolerant to sedimentation compared to rocky-shore macroalgae. Furthermore, in

accordance with the studies by Roos et al. (in press), *Fucus vesiculosus* was favoured by ferryboat traffic in our study and this is most probably related to increased resuspension partly freeing scattered rocky substrates from sediment in the sheltered inlets. That sediment cover significantly reduces the recruitment of *F. vesiculosus* in the Baltic Sea has been shown both in field- and laboratory experiments (Berger et al., 2003; Eriksson and Johansson, 2003).

The type of inlets surveyed in the present study is highly significant as recruitment and feeding areas for coastal fish in the Baltic Sea. Year-class strength of the majority of coastal fish species is strongly dependent on reproductive success and survival during the first year of life (Kjellman et al., 2000, 2003; Houde, 1997). The quality of their recruitment and feeding areas are therefore of fundamental importance for the structure of the adult commercially utilised stocks. Access to suitable vegetation as spawning substrate and structural refuge for young-of-the-year fishes has been deemed critical for near-shore fishes in both freshwaters and marine areas (Heck et al., 1989; Eklöv and Persson, 1995; Whitfield, 1984; Grenouillet and Pont, 2001). Effects of vegetation characteristics on fish recruitment has not been as thoroughly studied in brackish waters, but the limited number of available studies indicate that the availability of structural refuges are of major importance also here (Sandström and Karås, 2002b). Thus, the differences in macrophytic community composition and vegetative cover demonstrated in this study indicate that boating may have significant effects on the quality of shallow and sheltered inlets as recruitment areas for fish. In addition, macrophytic vegetation also supports species diversity of a number of other animal groups (Boström and Bonsdorff, 1997; Boström and Mattila, 1999), for example are many of the plants hosts to numerous species of invertebrates (Pihl, 1986; Wallström et al. 2000).

In conclusion, the present results provide correlative evidence that species-specific changes and negative impacts on species richness and coverage of aquatic vegetation are associated with both marinas for small boats and along ferryboat routes with medium-sized vessels. Since vegetation has a key role in sustaining faunal biodiversity in general and fish recruitment in particular, it is important to further investigate consequences of boating activities for the biological communities in the Baltic archipelagos. In particular, there is a need for experimental work to causally link changes in vegetation to boating effects that extends beyond the type of observational study reported here.

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